LISA Phase Measurement Technique

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ABSTRACT

The LISA mission will form the equivalent of a Michelson interferometric beat signal from the 1064nm laser beams traversing the inter-spacecraft arms. The design gravitational wave sensitivity requires measurement of round trip path differences for each detector to be about 10 pm/$\sqrt{Hz}$ over a frequency range from 10^{-4} to 10^{-1} Hz. Thus LISA's phasemeter must measure the beat signal phase to 10^{-5} cycle/$\sqrt{Hz}$ at 1mHz. Doppler shifts between spacecraft in their orbits are expected to range from 1 to 15 MHz. Phase measurement using the digital phase-locked loop approach incorporated in a modified TurboRogue® GPS receiver has been investigated in this study. It is found that only resolution in the range of 10^{-4} to 10^{-3} cycle/$\sqrt{Hz}$ at 1 mHz is achievable with this hardware. Abrupt fluctuations in the phase measurement at the millicycle level are responsible for the limitation.

Keywords: phasemeter, LISA, GPS, TurboRogue®

1. INTRODUCTION

The goal of the Laser Interferometer Space Antenna (LISA) [1] mission is to detect gravitational waves from massive black holes and galactic binaries in the frequency range from 10^{-4} to 10^{-1} Hz. This range complements that which ground-based detectors such as LIGO can address (10-10k Hz). The baseline design for the mission calls for three identical spacecraft to fly in an equilateral triangle formation with 5×10^9 meter separation. Spacecraft separation will be measured interferometrically using Nd:YAG laser beams of wavelength 1064 nm. The optics to communicate with the other members of the constellation are mounted on two optical benches on-board each of the spacecraft. Each bench has a layout as shown in Figure 1.
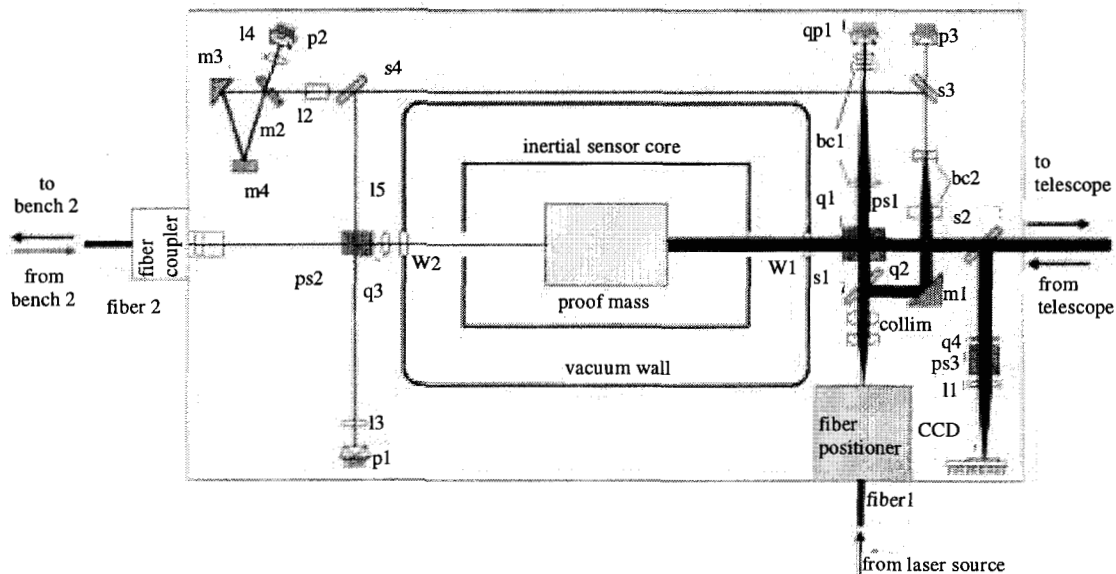

Figure 1. LISA Optical Bench Layout from Ref. [1].

A detailed discussion of the LISA optical system may be found in Reference 1. Only the aspects relevant to this discussion will be summarized here. Light from the laser source enters on fiber 1. 99.5% of the beam's power is directed by the polarizing beamsplitter, ps1, to the telescope for transmission to the far spacecraft. The remaining 0.5% of the power is compressed onto the active area of the quadrant photodiode, qp1. Laser light from the distant spacecraft is collected in the telescope and directed onto beamsplitter, s2. A small fraction (5%), is used for remote spacecraft detection by the CCD while 95% of the light reflects from the proof mass and is routed to qp1 by ps1 where the beat signal is formed by its interference with the local beam. The heterodyne signal passes to the interferometer electronics where the phase of the beat signal is measured by the phasemeter.

Requirements on phasemeter performance are quite stringent. The photoelectron shot noise limitation for each detector has been capped at about 10 pm/$\sqrt{\text{Hz}}$ which corresponds to 10^{-5} cycle/$\sqrt{\text{Hz}}$. A cancellation scheme will address the issue of laser phase noise at low frequencies which has been estimated to be 2×10^4 radians/$\sqrt{\text{Hz}}$ at 1 mHz. Consequently the dynamic range for the phase measurement spans nine orders of magnitude.

Quadrant Photodiode

Transimpedance Amplifiers

Laser Phase Lock Signal

Σ

Multiplier 200 MHz — USO Signal

USO Signal — NPO 0.1 - 15 MHz

Tracking Filters 10 kHz 5 kHz BW

0V 0V 0V 0V   0V 0V

Comparators

Phase Difference and Wavefront Tilt

Period Counter (Doppler Shift) — Laser Frequency Lock Monitor

Digital Filter

Digital Filter

Digital Filter

Wavefront Tilt

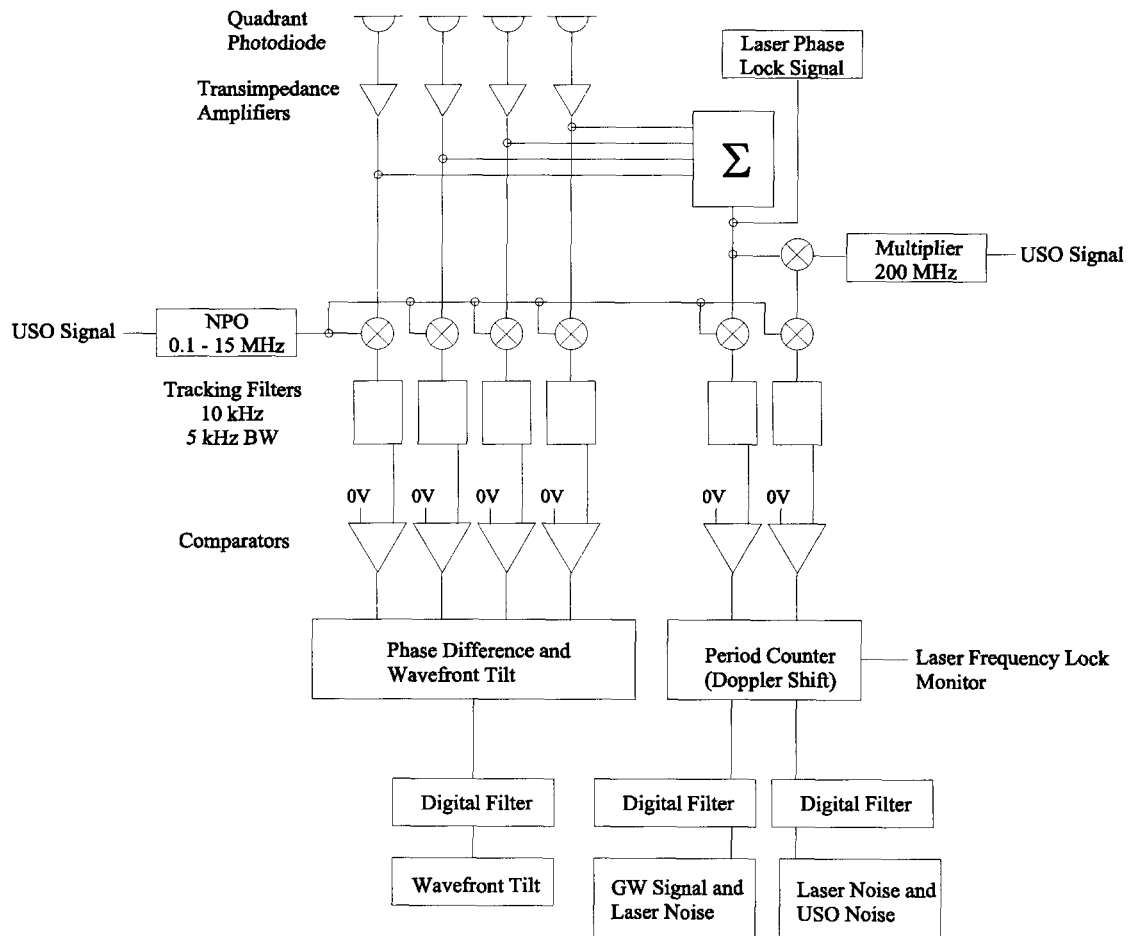GW Signal and Laser Noise

Laser Noise and USO Noise

Figure 2. Baseline LISA interferometer electronics schematic.

The baseline interferometer electronics schematic is shown in Figure 2. Heterodyne signals from the quadrant photodiode are amplified and beat against a reference signal produced using a 32-bit Direct Digital Synthesizer (DDS) driven by the Ultra-Stable Oscillator (USO). Doppler frequency variation is thereby removed and the resulting signal has a frequency in the range of 8-12kHz. Laser frequency noise is reducible by appropriate choice of the beat frequency. Phase noise above 1kHz is removed by the tracking filter. Anti-aliasing filters will also clean the signals at this point.

Signals are digitized in the comparators and then input to the phasemeter. The baseline phasemeter is a zero-crossing counter type using the USO signal for the clock input. The zero-crossing scheme is favored since it is less sensitive to temperature-induced gain fluctuations. Two phasemeter architectures are considered as candidates – either a fully digital phase lock loop (DPLL) system or a hybrid digital and analog PLL. This study concerns a DPLL implementation in the form of a modified TurboRogue® GPS receiver.

2. GPS RECEIVER

In contrast to the zero-crossing counter technique is one in which a model of the signal is compared against the input. A digital phase-locked loop can be schematically represented as in Figure 3 as a counter-rotation processor (CP) followed by a tracking processor (TP) [3] which operate at different rates. The input RF signal is sampled in quadrature mode at a uniform rate, f_S. In the CP, the signal is complex multiplied with counter-rotation phasors, the model signal, generated by the numerically controlled oscillator (NCO). The phasors result from feedback provided by the TP. The products are summed over an interval, T' [1], to produce average counter-rotated phasor components, U_I and U_Q, in-phase and 90 degrees out of phase relative to the NCO phase, respectively. U_I and U_Q are passed from the accumulator to the TP at the update rate, $1/T \ll f_S$, where they are used to compute a residual phase, $\delta\phi$. The residual phase is used in turn to estimate a model phase rate in the Loop Filter. Finally, the phase rate determines the model phase, ϕ_m, which is fed back to the CP's NCO. The loop is in lock when the feedback drives the phase and phase rate values to zero. The TP accumulates integer and fractional cycles. The fractional cycle is used by the NCO to generate the counter-rotation phasors. Output from the TP consists of measured phase and time tag for each interval. Since both phase and phase rate are being used to determine the feedback, this is a second order loop. A circuit such as this is part of the TurboRogue® GPS receiver.
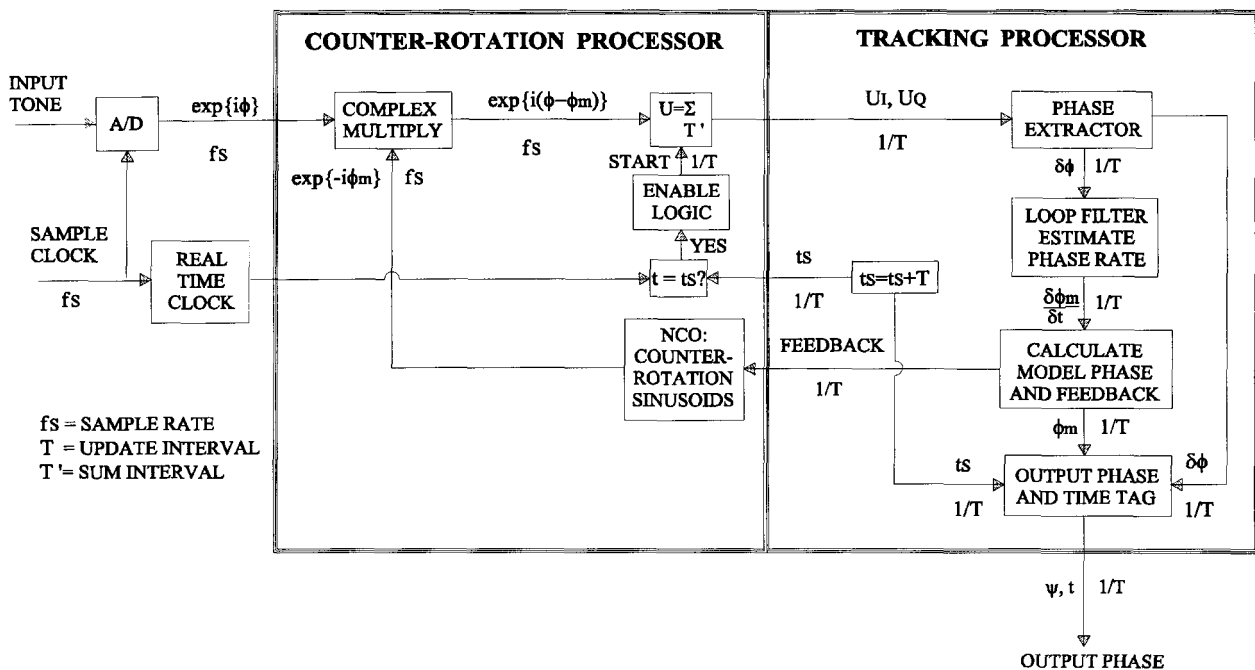

Figure 3. Digital Phase Locked Loop Circuit Schematic [3]

1. The sum interval, T', and the update interval, T, differ by the dead time between sum intervals. This difference is small.

The topic of Global Positioning System (GPS) receivers has been extensively documented [2 and references therein]. GPS receivers, in particular the AOA TurboRogue® [4], have been developed for both ground- and space-based applications and have a long heritage in both. Typically GPS signals are received by an antenna, amplified, passed through down conversion-digitization circuitry and processed by a baseband board. In the system used in this study, sinusoidal input signals were generated by RF synthesizers. The "front-end" circuitry was replaced with a two-channel prototype sampler circuit similar to that which is used in current-generation flight receivers. An 8-channel TurboRogue® baseband board was used for processing. Special firmware loaded onto the processor was specifically intended to perform a tone tracking function (typically used at Deep Space Network sites) as opposed to the normal GPS signal processing function. This ability to use a custom version of the firmware is unique among GPS receivers. An auxiliary file configured the receiver to use specific parameters for the tracking session: tone frequency, bandwidth, phase extraction technique, loop order, etc.

3. MEASUREMENT TECHNIQUE

A schematic of the experimental setup is shown in Figure 4. Two Agilent 33250A RF synthesizers were synchronized by locking their output phases. One synthesizer provided the tone signal to be tracked by the receiver while the second drove the 20.456 MHz clock input. The 0 dBm tone signal was split using a Mini-Circuits power divider (model ZFSC-2-6) and input to each of the sampler's two channels. By using the same signal source, common mode errors in the source are eliminated in the difference of the two phase measurements. The receiver was set up in a standard default configuration with registers holding historical information cleared. Tracking sessions were set to commence at a specific time. Efforts were taken to optimize system performance. Due to the sensitivity of some of the receiver components to temperature variations, data runs were taken during the times when the laboratory's climate control system was idle. This meant that the ambient temperature changed slowly during a run. Channels for data collection were selected to be on the same processor chip to reduce systematic variations. Data (tone frequency, accumulated phase, SNR, etc.) were logged to a flashcard at 1 Hz and offloaded at the completion of the run. Data were collected for signal frequencies ranging from 0.1-10MHz. Relative delay in the signal lines was introduced with fixed lengths of cable. Temperature data
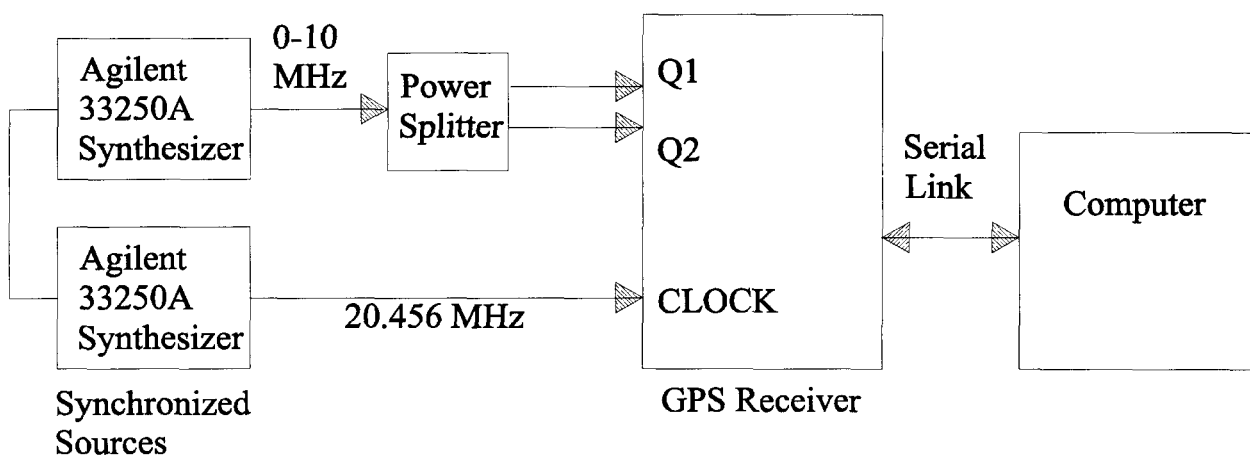

Figure 4. Schematic of experimental setup.

were collected from several points in the setup during the run. Analysis involved forming the difference of the signal phases and determining the spectral amplitude of the phase difference time series.

4. RESULTS

Figure 5 shows the time series of the phase difference between two channels of the receiver for a 5MHz input signal. There is a relative offset of roughly 0.015 cycle between the two channels. Since the cables used have identical lengths to less than a centimeter this channel-to-channel offset is simply a repeatable systematic feature of the receiver. The variation in the phase difference over time has a character seen in other data runs. Temperatures of the processor board and sampler module taken concurrently do not mimic the behavior. Since the temperature difference between the two locations is nearly constant it is difficult to suspect an effect dependent upon the temperature gradient. Despite the processor channels being configured in an identical fashion, plots of the variation in phase[1] for the individual tones (Figure 6) shows that the channels are behaving differently. Abrupt changes in phase with up to several millicycles magnitude are seen. Whether the cause for the abrupt changes is due to component variability or aging is not known. Due to complex packaging, it was not considered worth pursuing a more detailed sub-component investigation at this time.
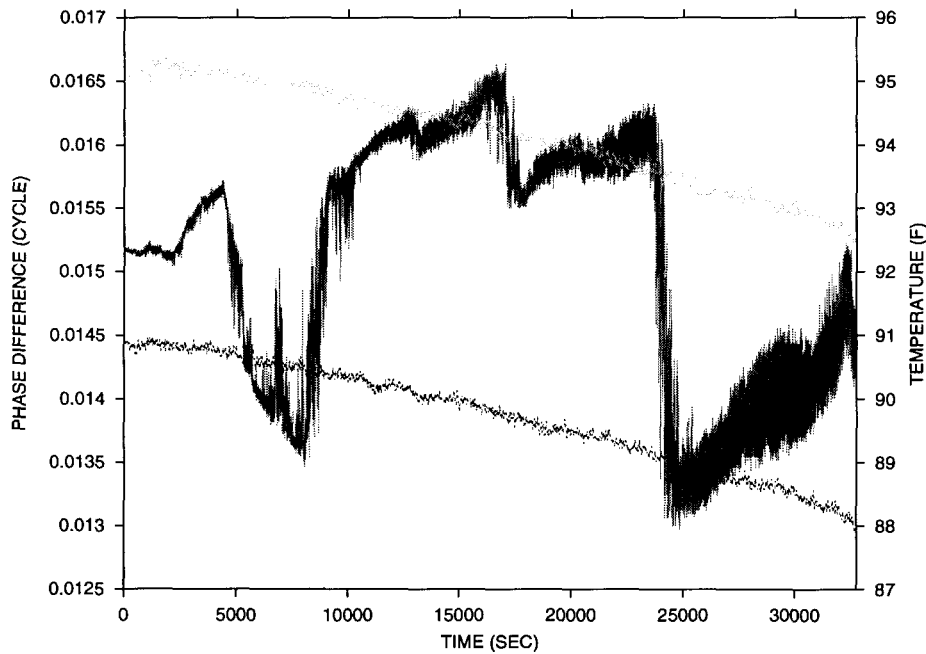

Figure 5. Time series of the phase difference between two receiver channels for a 5MHz signal. Also shown are the temperatures of the processor board (upper trace) and sampler module (lower trace) taken concurrently with the phase data.

The spectral amplitude of the phase difference[2] is shown on Figure 7. LISA's requirement of 10^{-5} cycle/$\sqrt{\text{Hz}}$ at 1 mHz is well below what this device can achieve. Spectral amplitudes as good as 10^{-4} cycle/$\sqrt{\text{Hz}}$ at 1 mHz have been obtained with this equipment.

1. The variation in phase is defined to be $\delta\phi(t)=\phi(t)-\phi(t_0)-t\times f$, where $\phi(t)$ is the measured value of phase at time, t, t_0 is the initial time and f is the frequency of the signal.
2. The spectral amplitude is taken to be the square root of the normalized power spectral density. The normalization factor is $f_s/2$.
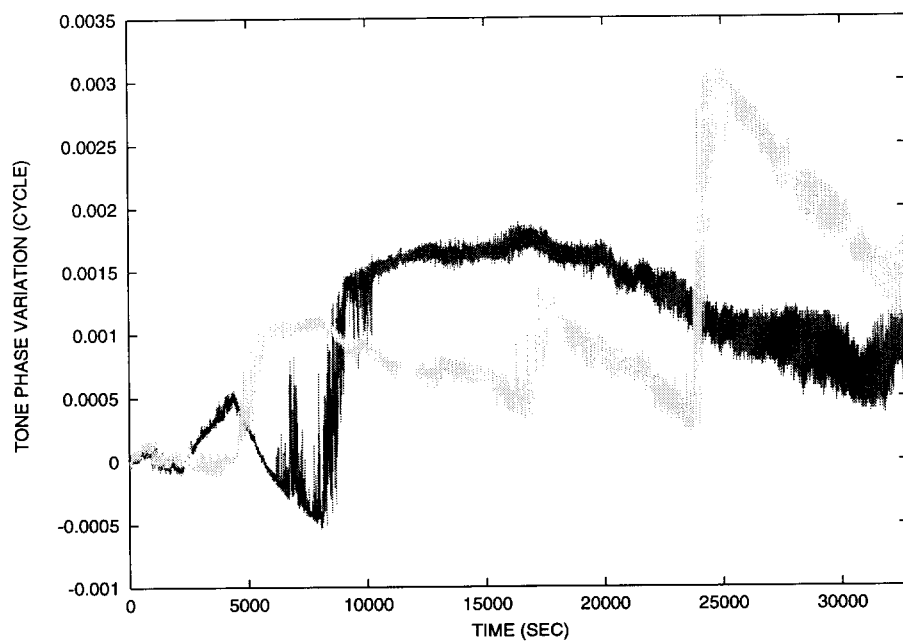
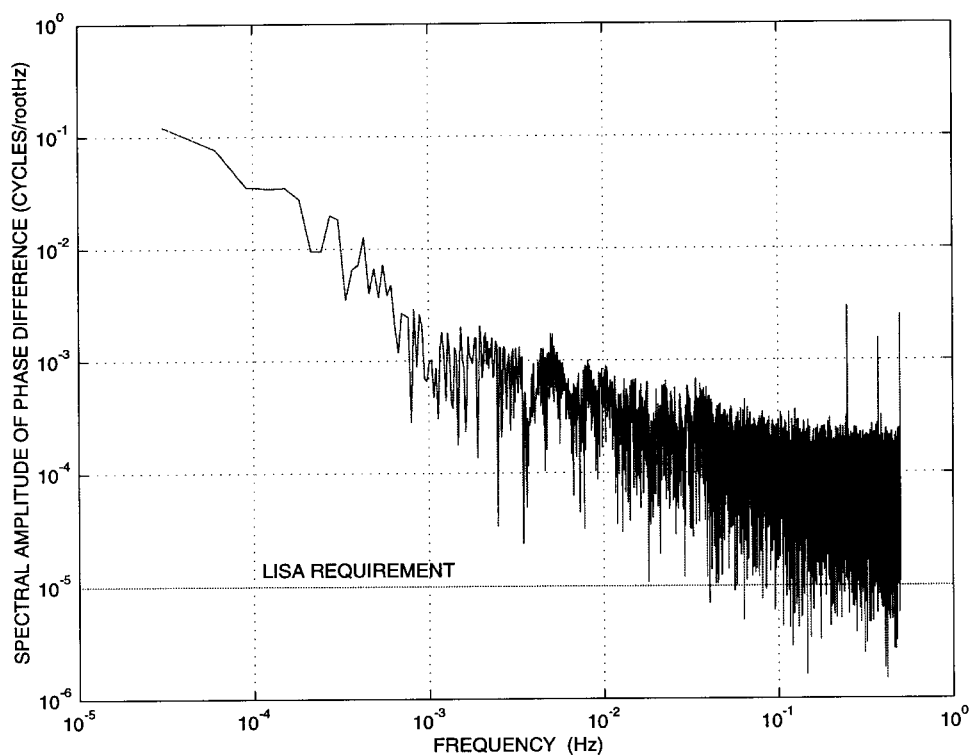Figure 6. The variation in the phase measurements for the separate tones.

Figure 7. Spectral amplitude for 5MHz input signal.

5. CONCLUSIONS AND FUTURE WORK

LISA's requirements for phasemeter performance are quite stringent. It was not expected that a receiver of the vintage of the TurboRogue® would be able to achieve such a goal. It was however thought that investigating the TurboRogue® would provide valuable experience in the interim while we considered acquiring a current generation receiver. Presently the acquisition of a commercial digital receiver system is under investigation. These units provide access to the latest generation of hardware at a cost well below what has been estimated for a nearly custom GPS receiver. The intent is to procure digital receiver system and carry out an evaluation in this technology development phase of LISA.

ACKNOWLEDGEMENTS

REFERENCES

1. LISA – Final Technical Report, No. LI-RP-DS-009, Dornier Satellitensysteme GmbH, et al. April 2000.
2. B.W. Parkinson and J.J. Spilker Jr. ed. *Global Positioning System: Theory and Applications, Volume 1.* Progress in Astronautics and Aeronautics, Vol 163, 1996.
3. J.B. Thomas. *An Analysis of Digital Phase Locked Loops*, JPL Pub 89-2, February 1989.
4. *The TurboRogue® Family of GPS Receivers User Manual*, December 1995. Allen Osborne Associates, Westlake Village, CA.
5. J.B. Thomas, *Signal-Processing Theory for the TurboRogue Receiver*, JPL Pub 95-6, April 1, 1995.

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